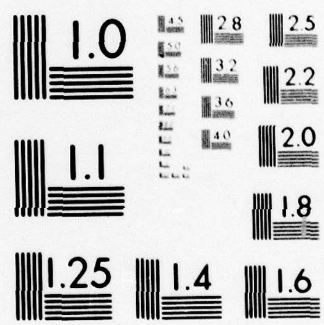
AD-A073 531 COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH F/G 13/2
CONSTRUCTION AND PERFORMANCE OF MEMBRANE ENCAPSULATED SOIL LAYE--ETC(U)
JUN 79 N SMITH
UNCLASSIFIED CRREL-79-16 NL

1 OF 1
AD
A073531

END
DATE
FILMED
10-79
DDC



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

(12) LEVEL II

CRREL

REPORT 79-16

Construction and performance of membrane encapsulated soil layers in Alaska

AD A073531

DDC FILE COPY

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

DDC
RECEIVED
SEP 7 1979
B

Cover: Bottom membrane and silty clay placement, Elmendorf AFB, Anchorage, Alaska. (Photograph by T. Marlar.)

14

CRREL [redacted]-79-16

CRREL

6

Construction and performance of membrane encapsulated soil layers in Alaska

10

North/Smith

11

Jun[redacted]79

12 34p.

16 4A762730AT42

17 A3

DDC
RECEIVED
SEP 7 1979
B

Prepared for
DIRECTORATE OF MILITARY PROGRAMS
OFFICE, CHIEF OF ENGINEERS
By
UNITED STATES ARMY
CORPS OF ENGINEERS
COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE, U.S.A.

Approved for public release; distribution unlimited.

037 100

79 09 4 105

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: CRREL Report 79-16
2. GOVT ACCESSION NO.:
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): CONSTRUCTION AND PERFORMANCE OF MEMBRANE ENCAPSULATED SOIL LAYERS IN ALASKA
5. TYPE OF REPORT & PERIOD COVERED:
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): North Smith
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire 03755
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: DA Project 4A762730AT42, Task A3, Work Unit 001
11. CONTROLLING OFFICE NAME AND ADDRESS: Directorate of Military Programs, Office, Chief of Engineers, Washington, D.C. 20314
12. REPORT DATE: June 1979
13. NUMBER OF PAGES: 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Anchorage, Alaska	MESL — membrane encapsulated soil layer
Cold environments	Polyethylene
Fort Wainwright, Alaska	Soil moisture migration
Membranes	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In 1973 two membrane encapsulated soil layer (MESL) test sections were constructed into existing gravel surfaced roads at Elmendorf AFB and at Ft. Wainwright in Anchorage and Fairbanks, Alaska, respectively. The Elmendorf AFB MESL contains a silty clay soil and the Ft. Wainwright MESL contains a nonplastic silt. Both sections were constructed at soil moisture contents of approximately 2% to 3% below optimum for the CE-12 compactive effort. There were no indications of soil moisture migration during freezing in either test section and after-thaw field California Bearing Ratio values were nearly equal to values measured before freezing. There is growing evidence of a slight increase in the overall soil moisture content in the Elmendorf AFB MESL possibly from moisture entering through the single layer polyethylene CONT'

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (cont'd)

Cont. sidewalls which were not treated with asphalt emulsion. There is good evidence that the membrane of the same section might have received damage during a soil sampling operation which allowed localized moisture infiltration. A two-layer polyethylene membrane used in the Ft. Wainwright MESL is considered a more positive moisture barrier than the single sheet and a justifiable added cost for permanent construction.

PREFACE

This report was prepared by North Smith, Research Civil Engineer, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The work was funded under DA Project 4A762730AT42, *Design, Construction and Operations Technology for Cold Regions*; Task A3, *Facilities Technology/Cold Regions*; Work Unit 001, *Use of Frost Susceptible Soils in Roads and Airfields*.

D.A. Gaskin and E.F. Lobacz of CRREL reviewed the technical content of this report.

The author expresses his appreciation for the support of field personnel at the CRREL Alaskan Projects Office and the Alaska District Office, Corps of Engineers. The military personnel of the 23rd Engineers Battalion (Construction), Ft. Richardson, Alaska, are to be commended on their excellent support during the construction of the Elmendorf AFB test section.

The author also appreciates the efforts of D.L. Carbee, Chief, CRREL Soils Laboratory, and his staff for the laboratory testing.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

CONTENTS

ILLUSTRATIONS

TABLES

CONSTRUCTION AND PERFORMANCE OF MEMBRANE ENCAPSULATED SOIL LAYERS IN ALASKA

North Smith

INTRODUCTION

During the past 20 years, many reports[2-7, 15, 17] have been published on membrane encapsulated soil layer (MESL) construction techniques, waterproofing materials and traffic testing. A brief description of the MESL concept is given in Appendix A. The results of these studies were summarized in a MESL Users Manual[16] written by the U.S. Army Engineer Waterways Experiment Station and published by the U.S. Department of Transportation. However, MESL use in cold environments was still under investigation when this manual was published.

In 1970, CRREL constructed an expedient MESL road section in central Alaska to evaluate extreme cold environment effects on MESL performance.[14] The results of that field study, laboratory studies on soils,[9] membrane and adhesive materials,[11] and subsequent interim results from two more test sections in Alaska,[12, 13] led to a CRREL position paper[10] for interim guidance on MESL use in cold regions.

This report presents the results of field tests conducted on two permanent MESL road test sections constructed by CRREL in 1973 at Anchorage and Fairbanks, Alaska. In addition, it presents discussion on the construction techniques and the results of more extensive laboratory soil testing related to these field tests.

LABORATORY STUDIES

General

Disturbed samples of the Elmendorf AFB silty clay used in the MESL section on Elmendorf AFB at Anchorage were used for classification, compaction, freezing and California Bearing ratio (CBR) testing.[9] Classification, compaction, freezing and CBR tests were conducted on disturbed samples of the Fairbanks silt used in the Ft. Wainwright MESL section; the results are presented in Appendix B. Previous laboratory freeze test data obtained by other investigators[1, 8] are also included where appropiate.

Laboratory soil freezing rates as low as those expected in nature or lower are generally used to give the most critical conditions for frost-heave testing.

Elmendorf AFB silty clay

The grain size distribution curve and soil classification data for the encapsulated Elmendorf AFB silty clay are shown in Figure 1. Compaction curves and CBR test results obtained before freezing and after closed-system* freezing and thawing of the clay are shown in Figure 2.† The influences of molding water content, compactive effort and degree of saturation on heave during closed-system laboratory freezing of the clay with and without lime stabilization are shown in Figure 3[9]. The relationships between heave and after-thaw CBR for the clay with compactive efforts CE-26 and CE-55 are shown in Figure 4[9].

Although little heave (0-3 mm) occurred at water contents between ±2% of optimum for

*Closed-system freezing indicates the absence of the flow of free water to the sample during testing. The open-system freezing test is conducted with a constant supply of water (at 40°F) maintained at the base of the soil sample through a porous medium during the freezing cycle.

†CE 12, CE 26 and CE 55 are Corps of Engineers designated compactive efforts of 12,000, 26,000 and 55,000 ft-lb/ft³ (0.57, 1.24 and 2.63 MN-m/m³).

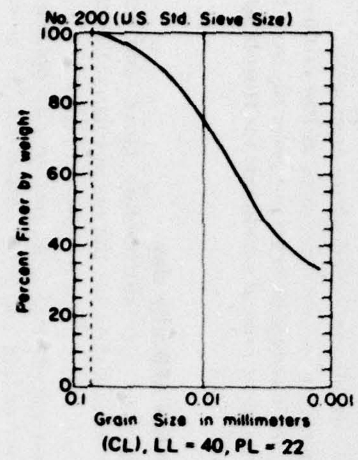


Figure 1. Gradation and classification of Elmendorf AFB MESL soil.

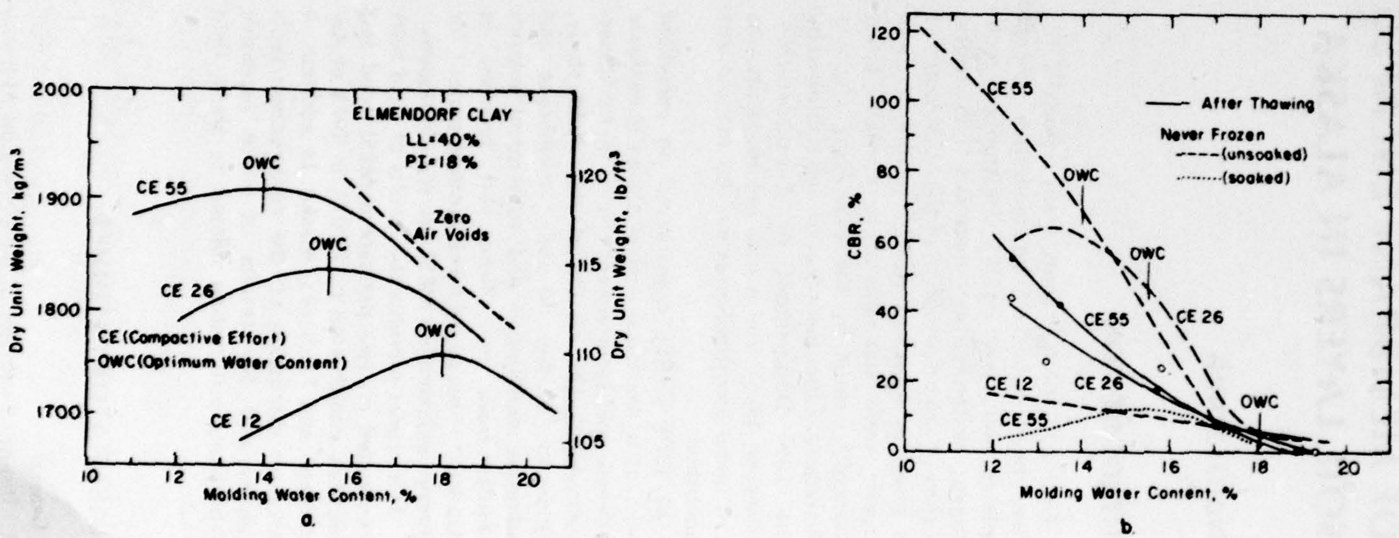


Figure 2. Soil compaction and CBR curves for Elmendorf AFB silty clay.

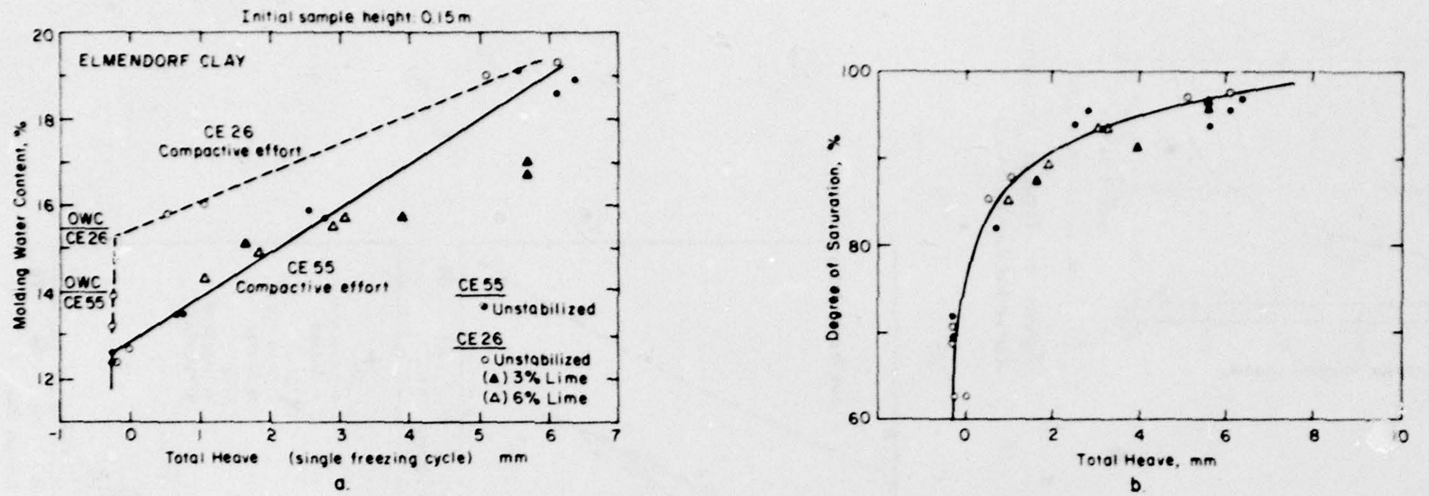


Figure 3. Influence of molding water content, compactive effort and degree of saturation on heave for Elmendorf AFB clay with and without lime.[9]

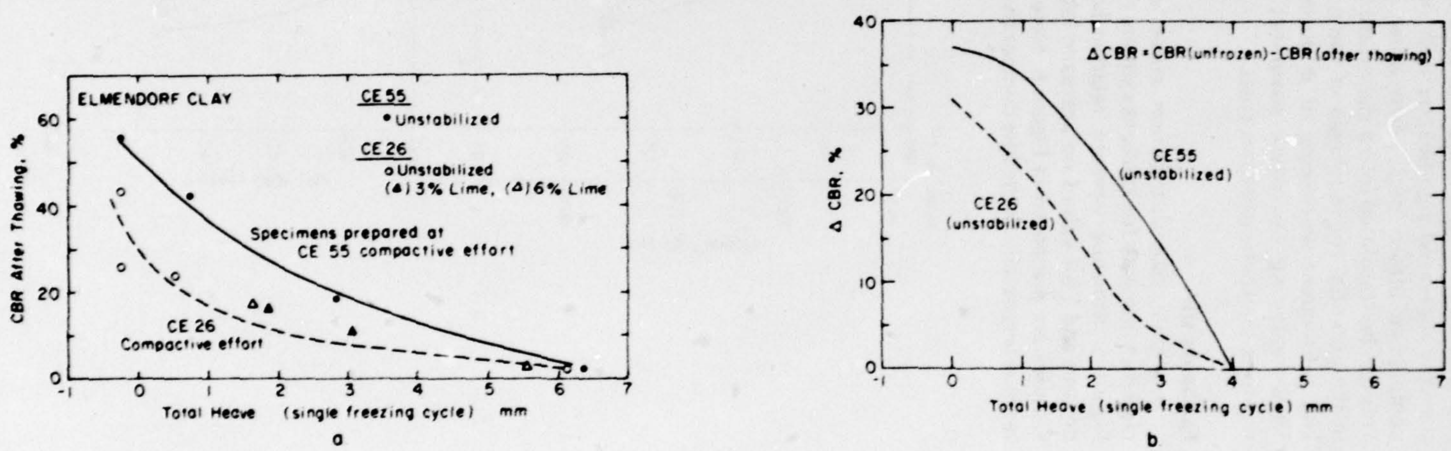


Figure 4. Interdependence of heave and after-thaw CBR for Elmendorf AFB clay.[9]

the clay (Fig. 3), the after-thaw CBR decreased dramatically with small increases in total heave (Fig. 4). Figure 3a shows that the total heave of the clay increased significantly with increased compactive effort for a given water content. This can be translated into a significant increase in the potential for roughness of the pavement and subsequent weakening of it during thaw. Thaw-weakening can cause pavement failures resulting in expensive repair costs.

Fairbanks silt

The grain size distribution curve and soil classification data for Fairbanks silt are shown in Figure 5. Moisture content relationships with density and CBR values on unfrozen laboratory samples are presented in Figure 6. Note the difference (especially at the low compactive effort)

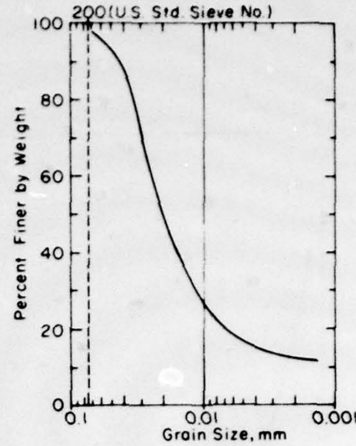


Figure 5. Typical gradation curve for Fairbanks silt.

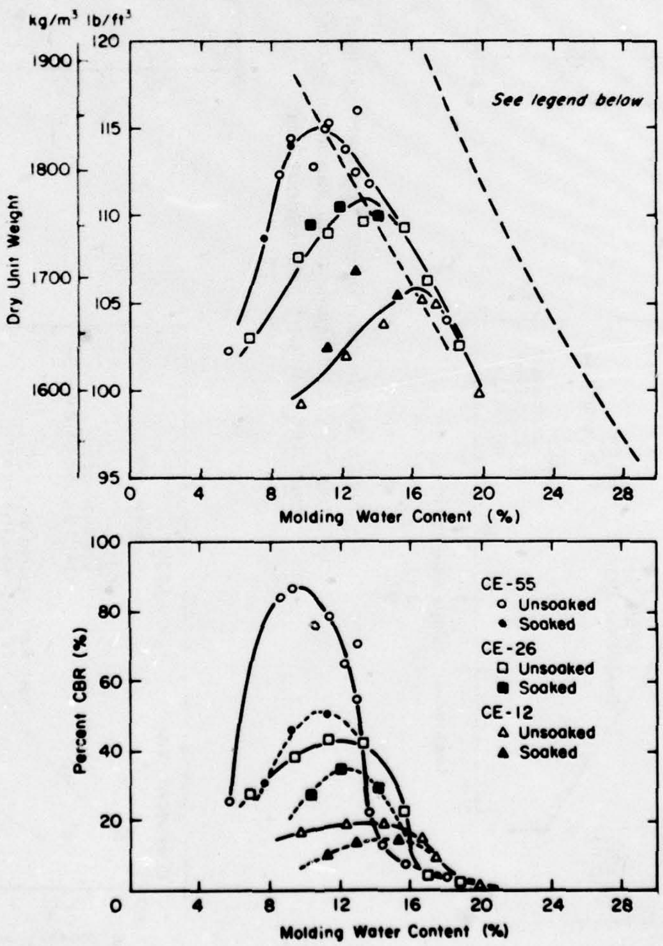


Figure 6. Soil compaction and CBR curves for Fairbanks silt.

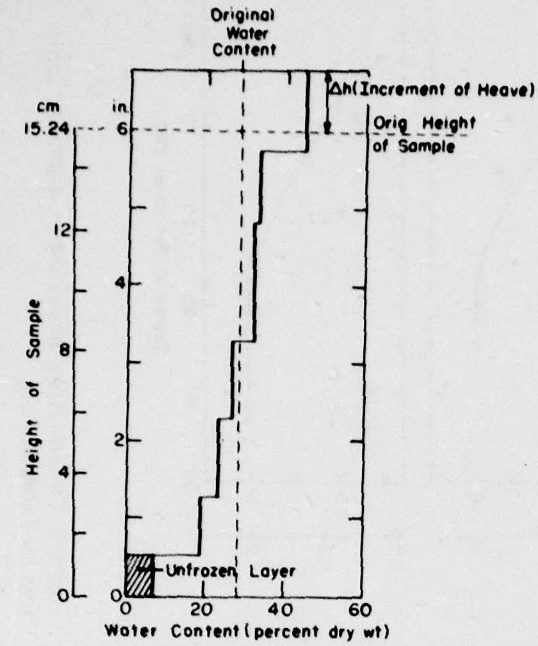


Figure 7. Water content versus depth for saturated Fairbanks silt.

between the optimum water content of the silt for maximum density and maximum CBR values. Earlier investigative results of a closed-system laboratory freeze test on an undisturbed subgrade sample of 100% saturated Fairbanks silt at a freezing rate of 0.25 in./day (6.4 mm/day) are reported in reference 1. These results showed that total heave occurred in about 12 days and amounted to 15.1% of the original 6-in. (152-mm) sample height, or 23 mm. The moisture redistribution in the sample after freezing ranged from 6.8% in the bottom unfrozen zone to 45% in the top inch (25.4 mm) as compared with a uniformly distributed 26.8% before freezing (Fig. 7). The prefreeze moisture content of the sample was determined from companion disturbed samples. The dry density of the sample was 97 lb/ft^3 (1553.8 kg/m^3), the void ratio was 0.717, and 40% by weight of the sample was finer than 0.02 mm. No strength tests were reported in these studies.

Several closed-system laboratory freezing tests at a freezing rate of 0.25 to 0.75 in./day (6.4 and 19.2 mm/day) and subsequent CBR tests on thawed samples of Fairbanks silt were conducted by Peyton et al.[6] in conjunction with soil stabilization tests. The samples were compacted at an effort of 56,000 ft-lb/ft^3 (2.68 MN-m/m^3) in 6-in. (0.15-m)-diam and 6-in. (0.15-m)-high CBR molds modified with tapered Lucite inserts to minimize edge restraint on heave. The maximum heave occurred in a sample with 100% saturation after the sample was compacted at 18% water content. This heave was a minimal 8 mm, or 5% of the original sample height; however, the after-thaw CBR value was essentially nil, indicating high moisture migration to the top of the sample.

A more extensive laboratory testing program was undertaken at CRREL to examine the relationships of molding water content and degree of saturation with total heave and after-thaw CBR values during closed-system freezing of the silt. The complete results of these tests are contained in Appendix B. Figures 8-11 are graphs developed to show these relationships. (The solid lines in the graphs are merely anticipated trends, not empirical curves.) Figures 8 and 9 relate total heave of the silt with molding water content and degree of saturation, respectively. As was seen in Figure 3a for the Elmendorf Clay, the total heave for the silt also is greater for increased compactive effort, especially at the higher water contents (Fig. 8). Likewise, as for the clay (Fig. 3b), the total heave for the silt is nearly a constant amount for a given degree of saturation regardless of compactive effort (Fig. 9). At a degree of saturation of 70%, the total heave for the samples is a relatively insignificant 3% of the original 6-in sample height.

Figure 10 shows that the after-thaw CBR value for the silt with high moisture content is greatest for the CE-12 compactive effort. The maximum after-thaw CBR value for the silt occurs at a moisture content below the optimum water content (OWC) for maximum dry density for all compactive efforts as is true for the samples that were unsoaked and never frozen (Fig. 6). The maximum increases in after-thaw CBR values gained by compacting at below optimum moisture contents are about 8, 9 and 1 for the CE-12, CE-26 and CE-55 compactive efforts, respectively. However, if the in-situ soil were dried to a moisture content of 12%, gains in after-thaw CBR values of about 11 and 24 would be realized by compacting at the CE-26 and CE-55 compactive efforts, respectively, rather than by compacting at the CE-12 compactive effort. Figure 11 shows the drastic decrease in after-thaw CBR values of the silt at saturation levels above 70% for the CE-26 and CE-55 compactive efforts.

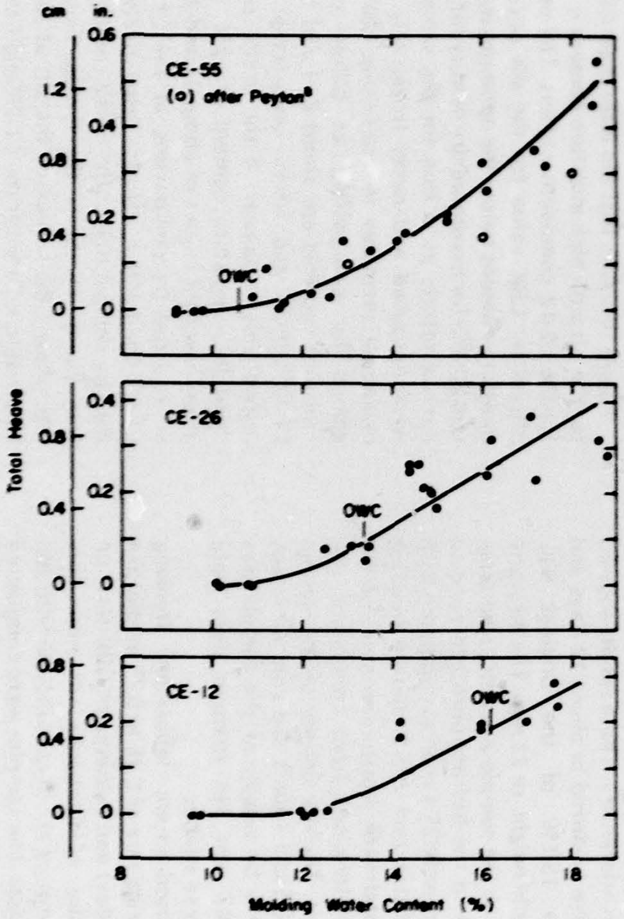


Figure 8. Closed-system heave versus water content for Fairbanks silt.

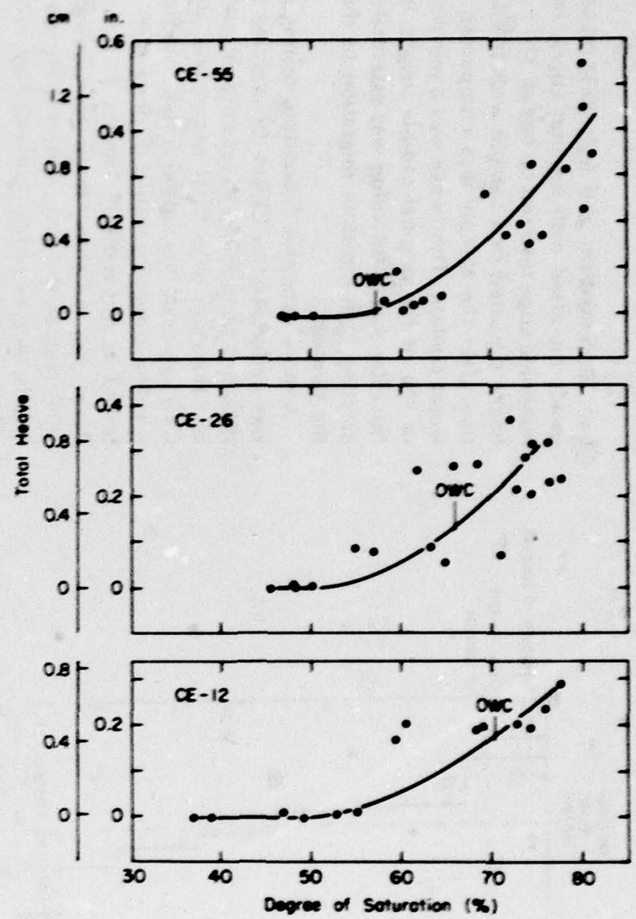


Figure 9. Closed-system heave versus degree of saturation for Fairbanks silt.

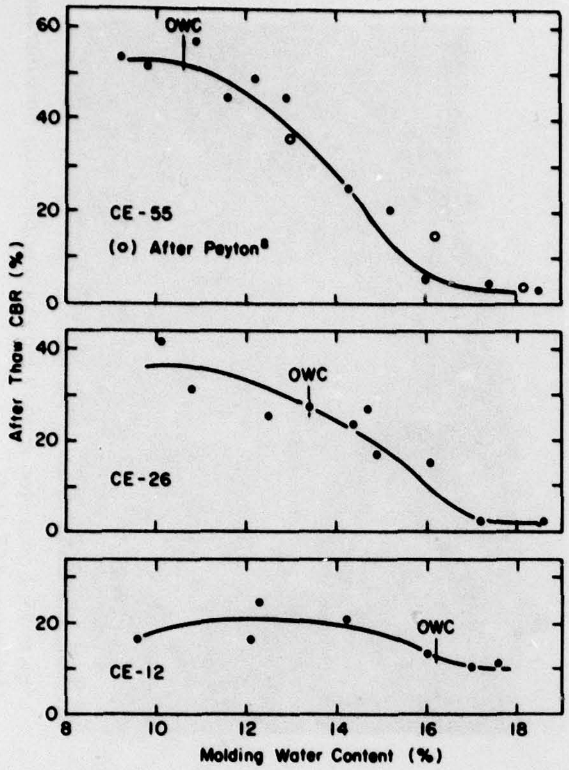


Figure 10. After-thaw CBR values versus water content for Fairbanks silt closed-system freezing.

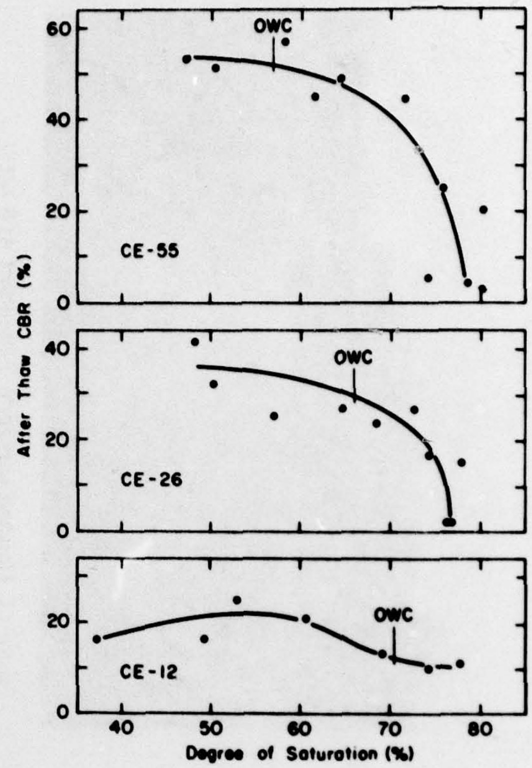


Figure 11. After-thaw CBR values versus degree of saturation for Fairbanks silt closed-system freezing.

FIELD STUDIES

Elmendorf AFB MESL

In June 1973, a 300-ft (91.4-m) portion of an existing unpaved, gravel-surfaced road was excavated to a depth of approximately 2.5 ft (0.76 m) and a width of 20 ft (6.10 m), utilizing military equipment and operators (Fig. 12). The subgrade was shaped with a grader and compacted with a 13-wheel, 9-ton (8165-kg) rubber-tired wobbly-wheeled roller. The finished subgrade is shown in Figure 13. Moisture contents in the subgrade at two locations and at depths of 3, 3, 5 and 6 ft (0.9, 0.9, 1.5, and 1.8 m) were 17.5, 21.8, 34.0 and 26.6%, respectively. The ground water table was about 5 ft (1.5 m) below the top of the subgrade. Subgrade soils ranged from coarse to fine gray sand with brown clay at near-saturated moisture contents at the greater depths. A field density test run on the subgrade surface after compaction indicated a dry unit weight of 141 lb/ft^3 (2259 kg/m^3) at a moisture content of 3.4%. The soil material at that location was a relatively dry silty fine gray sand.

Hot asphalt emulsion (Asphalt Institute Designation CRS-2) was sprayed onto the subgrade by a distributor at a temperature of 140°F (60°C) and an application rate of 0.3 gal./yd^2 (1.36 liters/m^2) (Fig. 14 and 15). This serves as a sealant under the bottom membrane in the event of a puncture during construction of the MESL section and is very helpful in holding the membrane in place during windy conditions. The bottom membrane, 6-mil (0.0254-mm)-thick polyethylene, was placed in 100-ft (30.5-m) lengths with 1-ft (0.3-m) overlapping transverse joints and in widths sufficient to provide a 2-ft (0.6-m) overlapping longitudinal joint with the top membrane.

An initial 1-ft (0.3-m) layer of silty clay was placed on the bottom membrane with front-end loaders from the end and down the middle of the

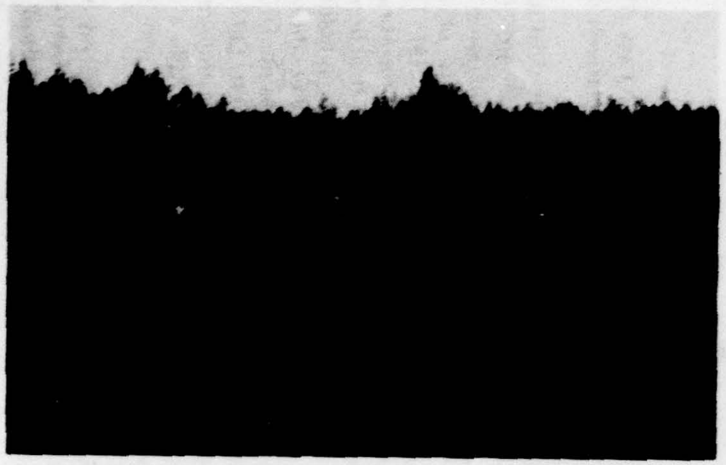


Figure 12. Excavating original road, Elmendorf AFB.

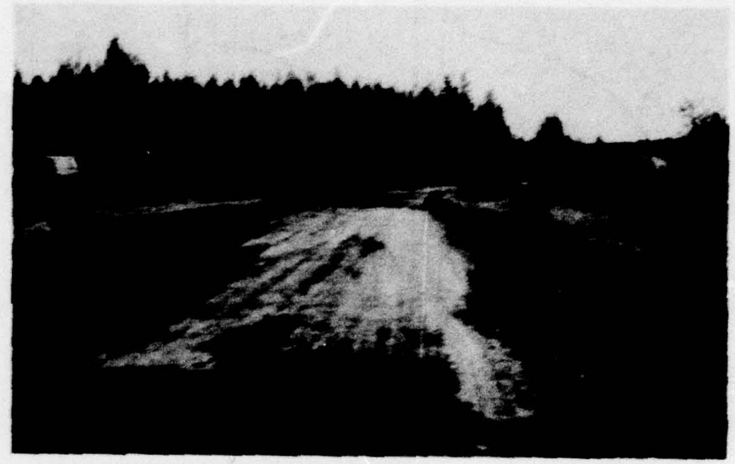


Figure 13. Finished subgrade, Elmendorf AFB MESL.

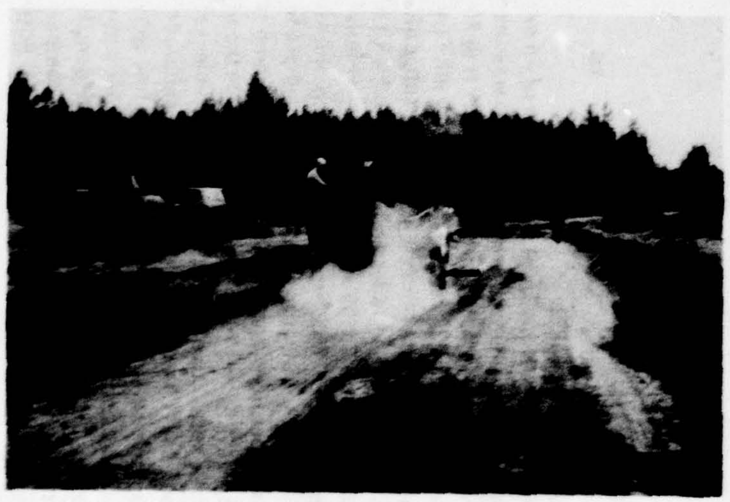


Figure 14. Asphalt emulsion application on subgrade, Elmendorf AFB MESL.

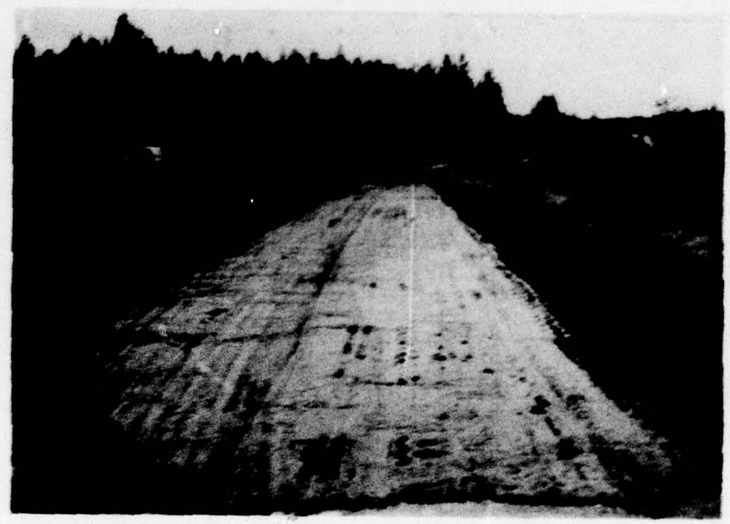


Figure 15. Completed asphalt emulsion application on subgrade, Elmendorf AFB MESL.

section to provide a travel surface for the scraper pans to complete the operation (Fig. 16 and 17). A road grader and sheep's-foot roller were used for spreading and compacting the fill (Fig. 18 and 19). Two additional layers resulted in a total fill depth of 2.5 ft (0.76 m). The final compaction of the fill before placement of the top membrane was accomplished with a wobbly-wheeled rubber-tired roller (Fig. 20 and 21).

Field CBR, soil moisture and density tests were conducted on the surface and about mid-depth of the fill at two locations immediately following final compaction. The results are given in Table I. The averages of six CBR values on the MESL surface and six at mid-depth have 18.0 and 16.3%, respectively. The averages of four dry densities and moisture contents at each of the same depths were 111.2 lb/ft^3 (1782 kg/m^3) at 16.4% moisture content and 105.2 lb/ft^3 (1686 kg/m^3) at 15.4% moisture content. The average moisture contents were below optimum and the average densities were 102 and 98% of the CE-12 compaction values at those moisture contents. The moisture contents represented 82% and 65% of complete saturation. Two strings of thermocouples were installed in the MESL fill and the underlying subgrade as shown in Figure 22. The string for the undisturbed location readings was installed in an auger hole beside the road and the instrumentation shelter was set up over it for protection against vandalism.

The surface of the fill was then sprinkled lightly with water to prevent balling of the asphalt emulsion in the dry surface dust. Asphalt emulsion was sprayed onto the surface at the same rate that was used on the subgrade, 0.3 gal./yd^2 (1.36 liters/m^2), before placement of the top membrane. The top membrane was made of nonwoven polypropylene fibers needle-punched on a polyester scrim, available in 300-ft (30.5-m) rolls, 15.5-ft (4.7-m) wide, with a unit weight of 3 to 5 oz/yd^2 (0.07 to 0.12 kg/m^2). Two lanes of the membrane with a 1-ft (0.3-m) longitudinal lap joint at the centerline provided sufficient width to make the lapped joints with the bottom membrane at the roadway shoulder line. Another application of asphalt emulsion (at the same application rate) was sprayed on top of the top membrane after the bottom membrane was folded up over the ends of the fill to make a sealed joint with the top membrane.

About 2 in. (51 mm) of clean sand was spread as a blotting and cushioning layer on the emulsion-coated top membrane before placing a 6 to 8-in. (0.15 to 0.20-m) gravel wearing surface of the previously excavated and stockpiled roadbed material. Final grading and compacting of the gravel surface with a road grader and the wobbly-wheeled roller were accomplished after the shoulders of the road and parallel drainage ditches were shaped and graded. The finished road is shown in Figure 23.

Following the first winter freeze, in 1973-74, soil temperature measurements indicated that frost had penetrated through the section to a depth of nearly 4.5 ft (1.37 m) into the underlying subgrade (Fig. 24). The average freezing rate during the 1973-74 winter was estimated from the ground temperature readings and average air temperatures (Fig. 24 and 25) to be about 0.5 in.

Table I. Field test results, Elmendorf AFB MESL fill.

Location	Depth from surface (in.)	0.2-in. CBR (%) Positions 1	2	3	Water content (%) 1	2	Wet density (lb/ft^3) 1	2	Dry density (lb/ft^3) 1	2
1	0	23	10	24	16.0	17.8	131 [2098]†	130 [2082]	113 [1810]	110 [1762]
	17 (0.43)*	13	8	18	14.1	14.3	123 [1970]	119 [1906]	108 [1730]	104 [1666]
2	0	15	15	21	16.1	15.9	126 [2018]	131 [2098]	109 [1746]	113 [1810]
	15 (0.38)	20	19	20	15.7	17.5	121 [1938]	122 [1954]	105 [1682]	104 [1666]

*( ) m.
† [ ] kg/m^3.

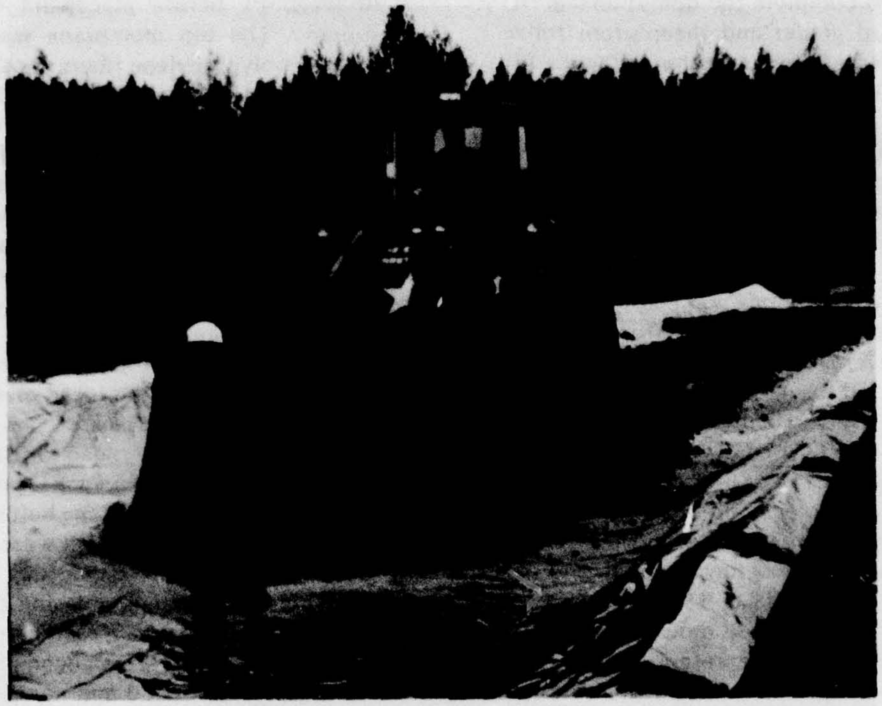


Figure 16. Placement of first layer of MESL fill, Elmendorf AFB.

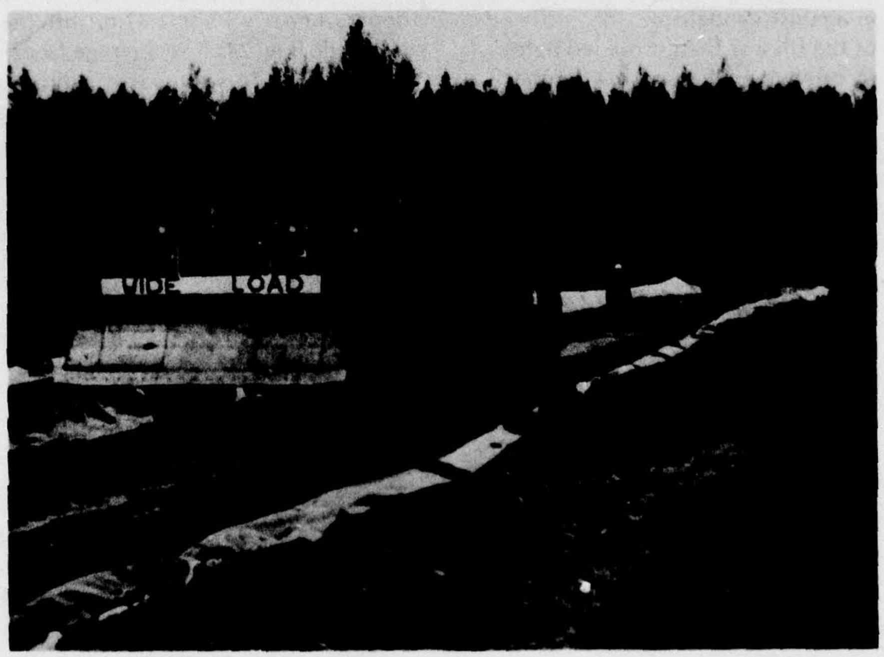


Figure 17. Completing placement of MESL fill, Elmendorf AFB.

Figure 18. Grading MESL fill, Elmendorf AFB.

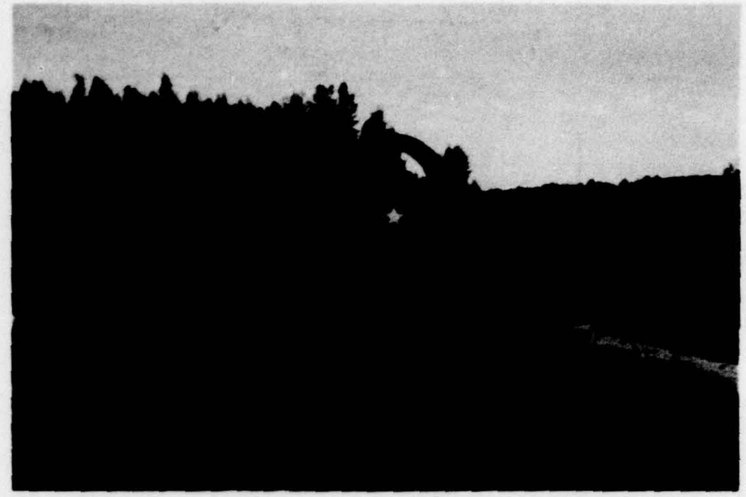


Figure 19. Compacting MESL fill, Elmendorf AFB.

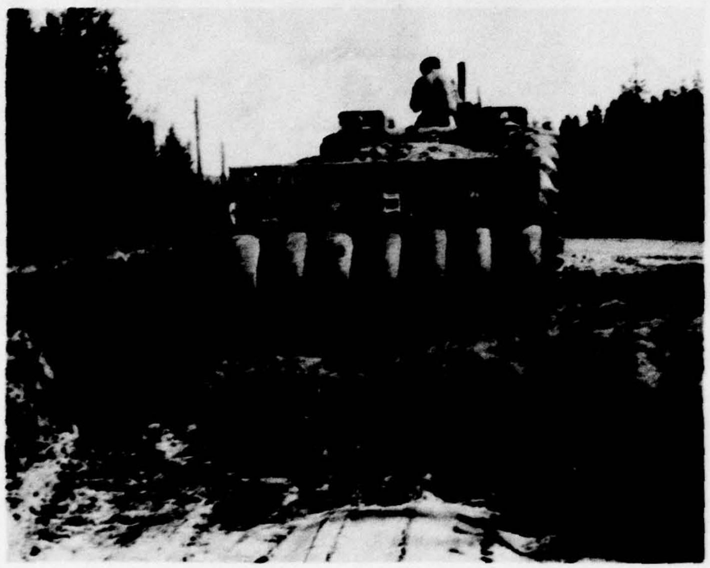


Figure 20. Wobbly-wheeled rubber-tired roller.

Figure 21. Completed MESL fill prior to placement of top membrane, Elmendorf AFB.

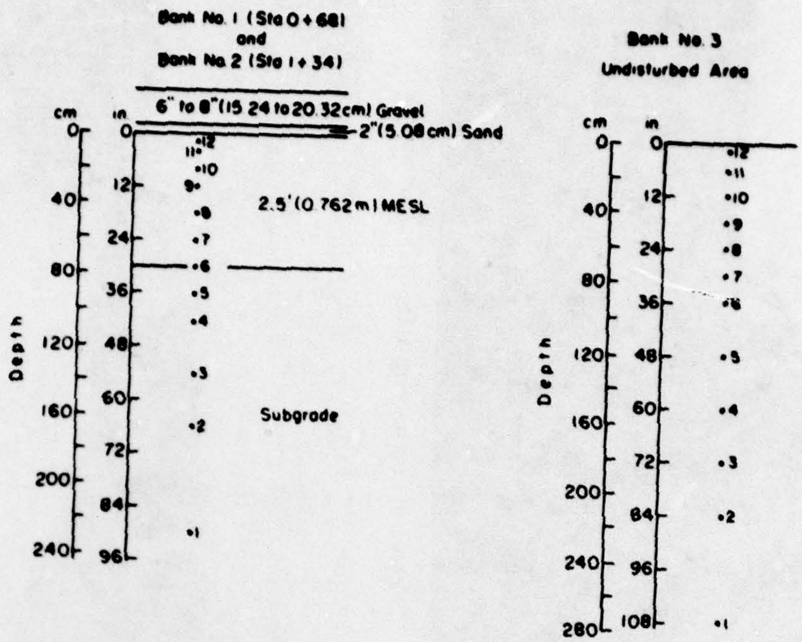


Figure 22. Thermocouple layouts, Elmendorf AFB MESL.

Figure 23. Completed MESL section, Elmendorf AFB.

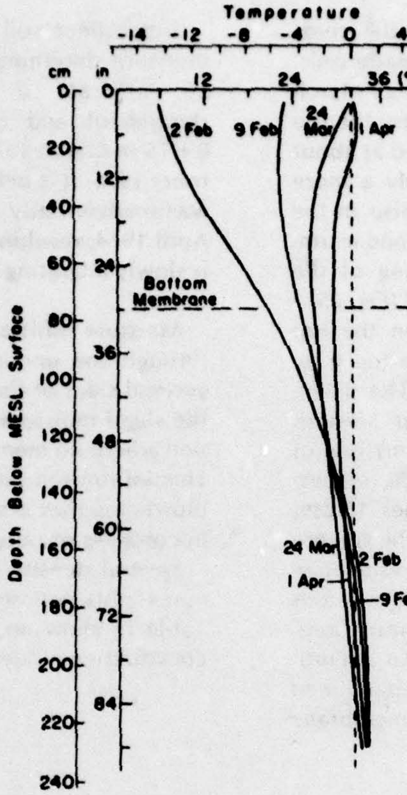


Figure 24. 1974 soil temperatures, Elmendorf AFB MESL.

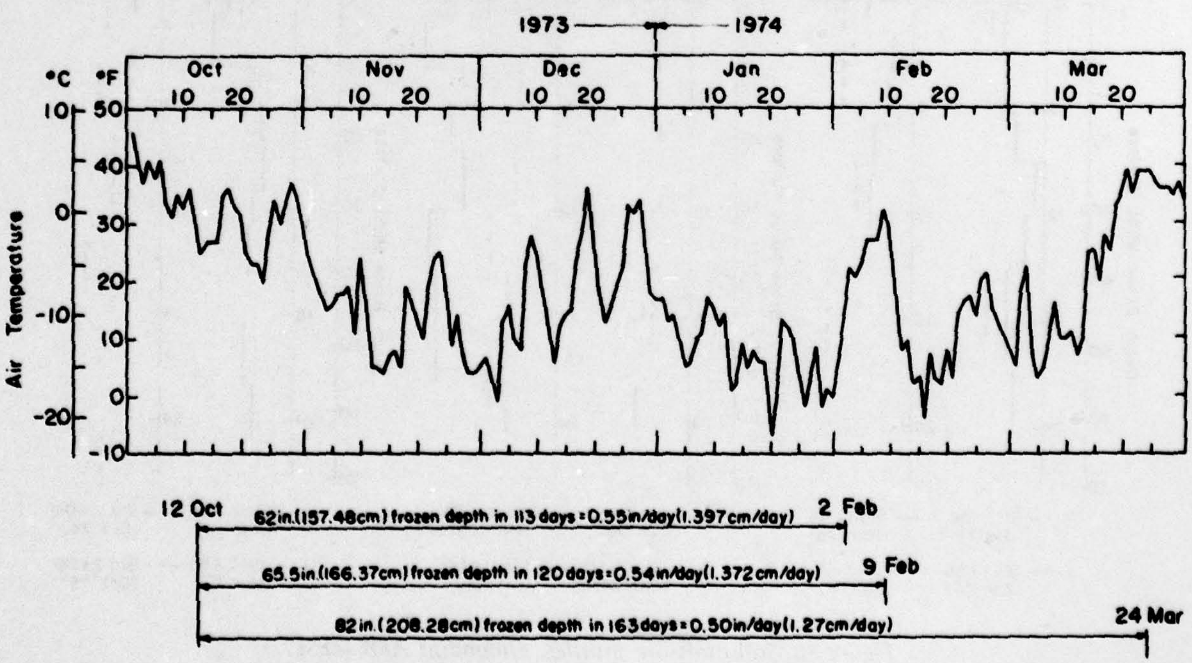


Figure 25. Average daily air temperatures and calculated soil (including subgrade) freezing rate, Elmendorf AFB MESL.

(12.7 mm)/day. However, this included the freezing of the high moisture content subgrade soils. From the soil temperature profiles for 24 March and 1 April (Fig. 24), the thawing rate for the top 8 in. (0.2 m) of MESL soil was calculated at about 0.9 in. (22.9 mm)/day. This is probably a more realistic value for the freezing rate also in the MESL soil alone, since the air cooling and warming rates at the beginning and ending of the freeze/thaw season were nearly equal (Fig. 25).

Three field CBR tests were run on the top membrane on 1 April 1974 when the top 9 in. (0.23 m) of the MESL was thawed. The 0.2-in. (5.1-mm) penetration CBR values at stations 0+75, 1+50 and 2+25, 4 ft (1.22 m) left of centerline, were 20.7, 17.9 and 15.9%, respectively. The average of these three values, 18.2%, is the same as the average value for the surface CBR values at the time of construction shown in Table I. Soil core samples were taken at stations 1+50 and 2+25 for moisture determinations. The results are plotted in Figure 26. An attempt at coring at station 0+75 was abandoned because of ponding water on the membrane beneath the gravel surface.

Subsequent soil samplings of the MESL for moisture determinations, also shown in Figure 26, indicate a slight moisture increase throughout and a major increase at station 0+75 in March 1975 and at station 1+00 in October 1976. It is believed that the top membrane was inadvertently damaged at station 0+75 in April 1974, resulting in moisture infiltration that is slowly migrating laterally from the point of entrance.

Moisture infiltration during the spring runoff through the uncoated polyethylene along the vertical sides of the MESL could be the cause of the slight moisture increase throughout the section where no membrane damage was apparent. This infiltration might be caused by very small blowholes that are inherent in the manufacturing process of polyethylene films.

Several density determinations made on soil cores obtained in March 1975, presented in Table II, show no increase in density from the construction values in Table I.

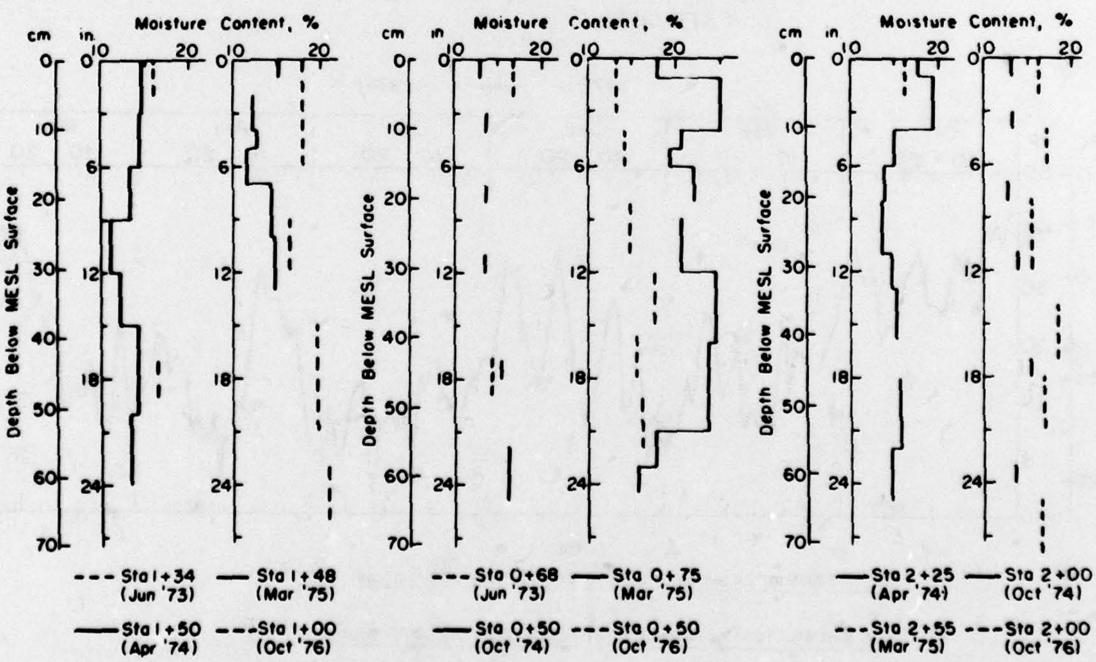


Figure 26. Soil moisture profiles, Elmendorf AFB MESL.

Table II. Elmendorf AFB MESL in-situ densities and moisture contents.

All samples contained some small pebbles.

Station	Depth (in.)	Dry unit weight (lb/ft^3)	Moisture content (%)
0+75	1 to 4 (0.02 to 0.10)*	115.8 [1855]†	25.0
	9 to 12 (0.23 to 0.30)	105.5 [1690]	20.6
	12 to 16 (0.30 to 0.41)	97.0 [1554]	24.7
	16 to 21 (0.41 to 0.53)	96.7 [1549]	23.8
1+48	10 to 13 (0.25 to 0.33)	108.8 [1743]	14.8

* ( ) m.
† [ ] kg/m^3.

Ft. Wainwright MESL

In September 1973, a nominal 2.5-ft (0.76-m)-thick silt MESL road test section, 20 ft (6.1 m) wide by 100 ft (30.5 m) long, was constructed into an existing unpaved gravel-surfaced road. The method of construction was essentially the same as described previously; however, the membrane material was different. A nylon-mesh reinforced two-ply polyethylene was used for both bottom and top membranes. These two features were considered necessary for a permanent long-term installation, since manufacturers' representatives reported that polyethylene film has some pin-holes when produced. The bottom membrane was a continuous sheet, 40 ft (12.2 m) wide by 100 ft (30.5 m) long, and the top sheet was 32 ft (9.8 m) wide by 100 ft (30.5 m) long. The asphalt emulsion was sprayed on the compacted subgrade and finished MESL fill at an application rate of 0.5 gal./yd^2 (2.27 liters/m^2) before placement of the membrane.

The silt was compacted in 4 to 5-in. (0.10 to 0.13-m) layers by about 10 passes of an 8-ton (7257-kg) wobbly-wheeled rubber-tired roller. Two density tests run on the top of the MESL fill indicated in situ dry-weight densities of 88.4 and 86.7 lb/ft^3 (1416 and 1389 kg/m^3) at a moisture content of 13.2% for both tests. These densities represented 85 and 84% of the laboratory compaction values for the CE-12 compactive effort at the 13.2% moisture content, which is about 3% below the optimum moisture content of 16.4%. Two CBR tests, also run on top of the MESL fill, indicated in-situ CBR values of 7 and 10%. The moisture contents of each silt layer are given in Table III. Approximately 3 in. (76.2 mm) of sand was spread on the top membrane before placement of an 8-in. (0.20-m)-thick river gravel surfacing.

Eight copper-constantan thermocouples were installed within the MESL, at the locations shown in Table IV, to monitor freezing and thawing. Four heat-flow meters were also installed within the MESL; however, meaningful data were not obtained from them.

Temperature profiles of the MESL during the first winter freeze-thaw cycle are shown in Figures 27 and 28. Both the freezing and thawing rates were approximately 1.5 in./day (38.1 mm/day) for that freeze-thaw cycle. The relatively high rates are attributed to the low moisture content and low density of the silt.

In-situ soil moisture content profiles are presented in Figure 29. Samples obtained in the frozen state (March 1975 and 1976) had moisture contents indicating uniform moisture distribution (no migration toward the top or freeze-front during freezing). The in-situ densities shown in Table V are for frozen samples taken in March 1975 and average slightly higher than the two measured at the time of construction (probably because of traffic compaction).

Table III. Moisture contents of Ft. Wainwright MESL fill when constructed.

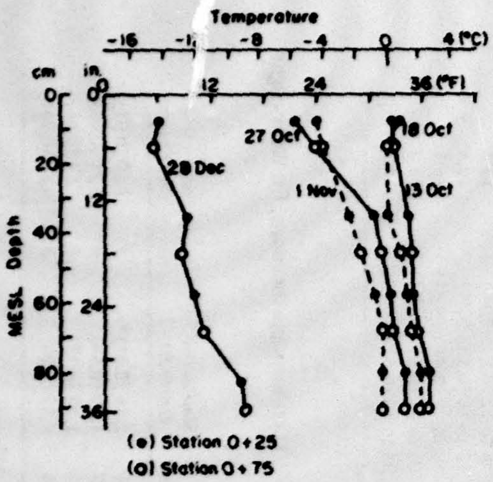
Depth (in.)	Moisture content (%)
0 to 4 (0 to 0.10)*	15.2
4 to 8 (0.1 to 0.20)	14.4
8 to 12 (0.2 to 0.30)	13.8
12 to 16 (0.3 to 0.41)	12.8
16 to 20 (0.41 to 0.51)	16.1
20 to 24 (0.51 to 0.61)	13.4
24 to 30 (0.61 to 0.76)	14.3

* ( ) m.

Table IV. Thermocouple locations, Ft. Wainwright MESL.

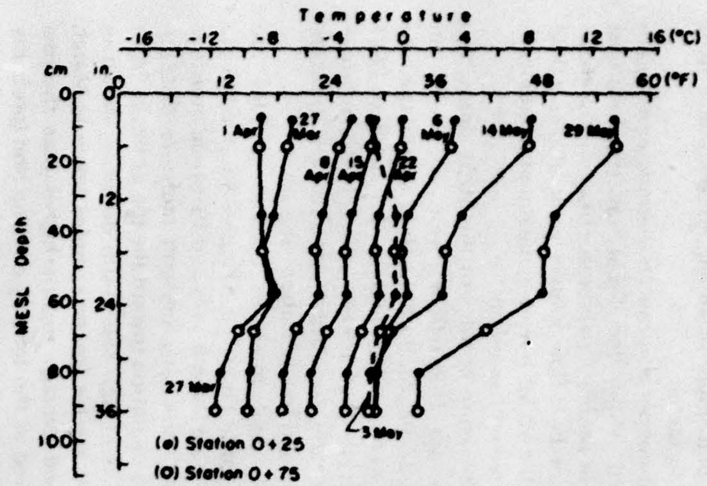
No.	Station 0+25 Depth (ft)	No.	Station 0+75 Depth (ft)
1	2.65 (0.81)*	5	3.00 (0.91)
2	1.90 (0.58)	6	2.25 (0.69)
3	1.15 (0.35)	7	1.50 (0.46)
4	0.25 (0.08)	8	0.50 (0.15)

* ( ) m.



Dates	Freezing rates
10/13–10/27	21 in./14 days = 1.5 in./day
10/18–10/27	13.5 in./9 days = 1.5 in./day

Figure 27. 1973 soil temperatures and calculated soil freezing rate, Ft. Wainwright MESL.



Dates	Thawing rates
4/22–5/6	20 in./14 days = 1.43 in./day
4/22–5/14	22.25 in./22 days = 1.01 in./day

Figure 28. 1974 soil temperatures and calculated soil thawing rate, Ft. Wainwright MESL

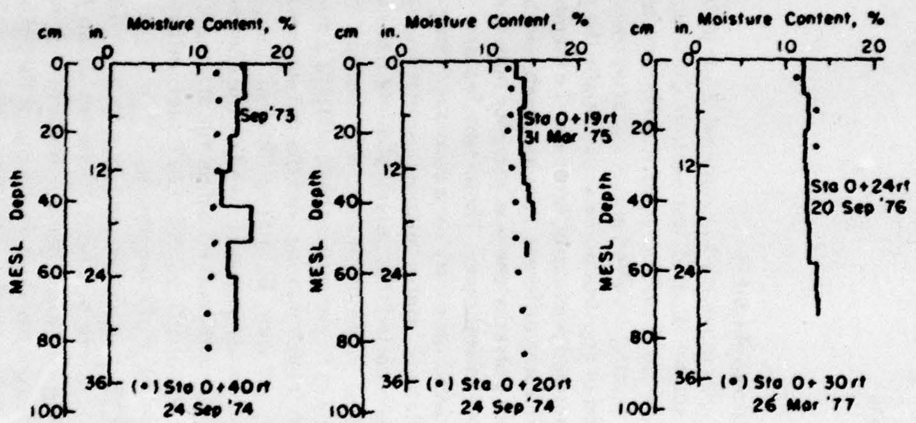


Figure 29. Soil moisture profiles, Ft. Wainwright MESL.

Table V. In-situ densities, Ft. Wainwright MESL, March 1975.

Depth (in.)	*Density (lb/ft³)*
0 to 2 (00 to 0.05)*	91.1 [1459]†
2 to 5.5 (0.05 to 0.14)	90.5 [1450]
14 to 16 (0.36 to 0.41)	88.5 [1418]
16 to 18 (0.41 to 0.46)	90.5 [1450]

* ( ) m.
† [ ] kg/m³.

TRAFFIC USE

Elmendorf AFB MESL

This MESL section is located in a gravel road used as an access road to a sand and top-soil borrow pit and a wooded recreational area. The types of vehicles utilizing the road range from minibikes to 10-ton (9070-kg) dump trucks. After construction in June 1973 and before winter freezeup, more than 400 loads of top soil and sand were hauled over the road, in addition,

Figure 30. Snow dump adjacent to Elmendorf AFB MESL.

Figure 31. Ponding snowmelt on Elmendorf AFB MESL (north view, upper; south view, lower).

Figure 32. Soil core sampling, Elmendorf AFB MESL, March 1975.

several thousand passes of mixed vehicular traffic were made over the road. During the wintertime the dump trucks hauling sand for sanding the streets and parking lots on the base use the road. However, the more critical loading periods are during and after spring thaw. The open area adjacent to the road is used as a snow dump during snow removal operations on the base throughout the winter (Fig. 30). This results in considerable water ponding in the parallel ditches and on the road surface during spring breakup (Fig. 31). Figure 32, a photograph taken during the soil coring operation of March 1975, shows a typical closeup of the surface spring meltwater conditions.

Ft. Wainwright MESL

This MESL section is located in a gravel road used daily by dumpster and garbage trucks. During the wintertime the road is heavily trafficked by passenger cars driven to and from the Birch Hill Ski Area. Since construction of the MESL, the Army has used the road as a haul road for construction equipment and as an access road to the sanitary landfill; Alyeska Pipeline Service Company also has used it to move pipe and equipment for pipeline construction (Fig. 33). The road surface has been sprayed with used engine oil to stabilize the river gravel and control dust. Springtime snowmelt conditions (Fig. 34) are not nearly as severe on this section as on the Elmendorf AFB section.

PERFORMANCE OBSERVATIONS

Elmendorf AFB MESL

This test section has maintained its integrity and only slightly increased in moisture content, except at one location where meltwater entered after an attempt was made to conduct a soil sampling operation. The moisture content profiles obtained from frozen core clay samples indicate that no moisture migration occurred because of the relatively low degree of saturation. Field CBR values during the spring thaw were the same as the prefreeze values during construction. In-situ densities remained essentially the same as when the test section was constructed.

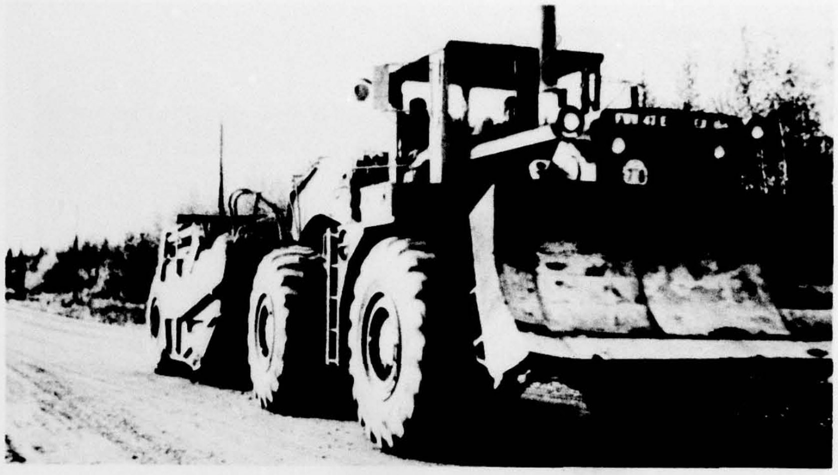
Ft. Wainwright MESL

This test section has shown no signs of distress. The very low original moisture content has been maintained and the moisture profile in the section in the frozen state has remained uniform. A slightly higher dry density obtained from frozen core sampling is attributed to traffic compaction.

CONCLUSIONS

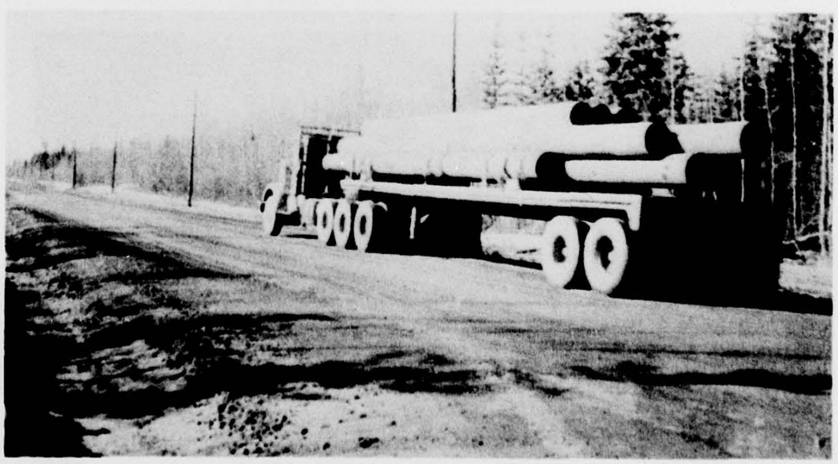
Elmendorf AFB MESL

The Elmendorf silty clay at an average moisture content of about 16% and an average dry density of about 111 lb/ft^3 (1778 kg/m^3) has



a. Construction equipment.

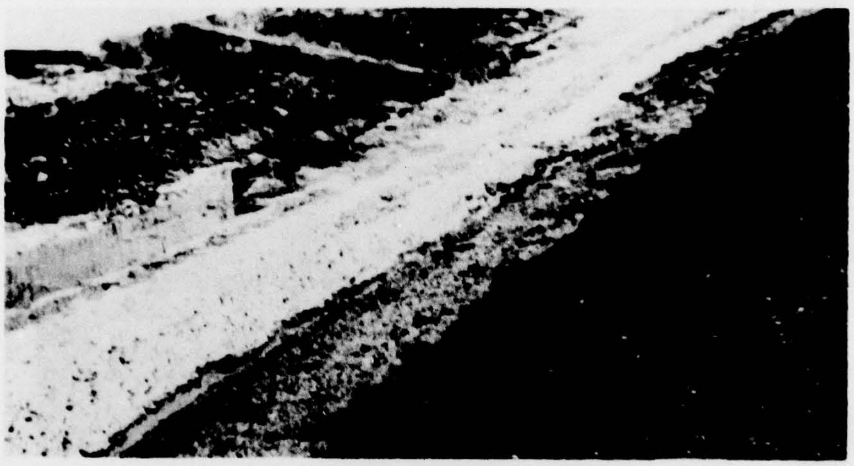
b. Dumpster truck.



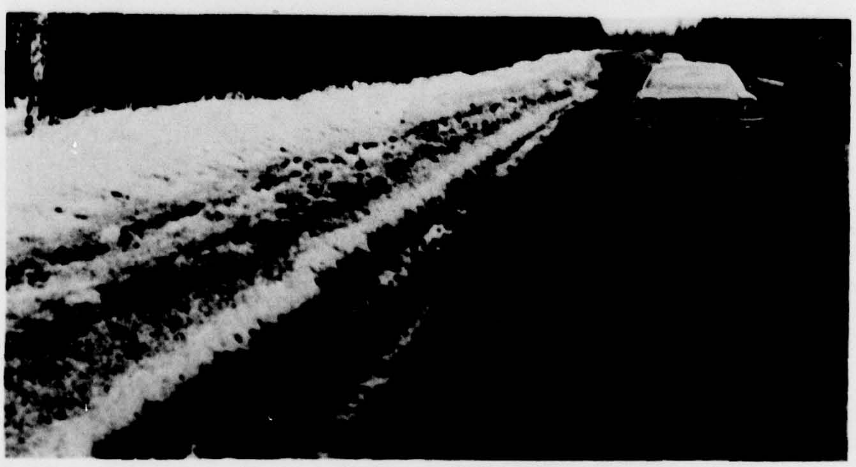
c. Oil pipeline pipe sections.

Figure 33. Vehicular traffic, Ft. Wainwright MESL.

a. Left parallel ditch.



b. Close-up of left parallel ditch.



c. Right parallel ditch.

Figure 34. Snowmelt, Ft. Wainwright MESL, April 1977.

maintained a uniform moisture profile during closed-system freezing in the MESL section at a freezing rate estimated at approximately 1.0 in. (22.9 mm)/day. The percentage of moisture saturation for the above moisture and density conditions is about 80%, which corresponds to a relatively low total heave (Fig. 3b).

The prefreeze and after-thaw CBR values for the Elmendorf silty clay were essentially the same, with an average value of 18.2%. With an 8- to 10-in (0.18 to 0.25-m) sand and gravel surface layer, the MESL with a CBR value in the range of 10 to 24% withstood low-density, light-vehicular traffic and occasional heavy truck traffic with minimal surface maintenance.

The near-vertical sides of the MESL, which are very difficult to spray adequately with asphalt, are a potential source of a long-term moisture increase because of very small blowholes in the 6-mil polyethylene inherent in the manufacturing process. A two-layer polyethylene provides better protection against this problem.

Ft. Wainwright MESL

The Fairbanks silt at an average moisture content of about 14% and an average dry density of about 88 lb/ft^3 (1427 kg/m^3) maintained a uniform moisture profile during closed-system freezing in the MESL section at a freezing rate of approximately 1.5 in. (38.1 mm)/day. The high freezing rate was due to the low moisture content and dry density. The percentage of moisture saturation for the above moisture and density condition was about 44%.

Traffic use of the MESL has increased its density about 3% from an average of 87.6 to 90.2 lb/ft^3 (1403 to 1445 kg/m^3). With the 8- to 10-in. (0.20- to 0.25-m) sand and gravel surface layer, the MESL with a CBR value in the range of 7 to 10% withstood medium-density, light-vehicular traffic and considerable heavy truck and construction equipment traffic with minimal surface maintenance.

The two-layer polyethylene membrane is considered an improvement over the single-layer membrane and probably is economically justified for permanent construction.

General

The drying of fine-grained soils for use in MESL construction can be a costly and difficult problem in some climates. It should be remembered that the lower the required density (compaction) the higher the moisture content can be and still have little moisture migration (heaving) during freezing (Fig. 8). Too much compaction effort, which is generally a rare occurrence, could cause a moisture migration problem with MESL construction and should be avoided if a lower density and higher moisture content material provides adequate strength (Figs. 6 and 10). The degree of saturation, which is lower at a given moisture content for lower densities, is the important factor when considering moisture migration (heaving) during freezing (Fig. 9). A multilayered MESL with the wetter (at or slightly above optimum moisture content) and less dense layer as a subbase separated by a horizontal cutoff membrane from a dryer, more dense top layer *could* save considerably on material drying and compaction costs.

Additional field tests with higher density soils are needed to determine moisture content and redistribution, heave, freezing rates and post-thaw strength relationships and to verify laboratory results.

LITERATURE CITED

1. Arctic Construction and Frost Effects Laboratory (1958) Frost investigations, Cold room studies. ACFEL Third Interim Report of Investigations, Technical Report 43. AD 217742.
2. Bell, J.R. and E.J. Yoder (1957) Plastic moisture barriers for highway subgrade protection. *Proceedings Highway Research Board*, vol. 36.
3. Burns, C.D. and V.C. Barber (1969-1971) Expedient surfacing and drainage of roads, streets and parking and storage areas in theater of operations. U.S. Army Engineer Waterways Experiment Station, Miscellaneous Paper S-69-11. Report 1, Tests conducted between July 1966 and August 1968, March 1969. Report 2, Tests conducted between August 1968 and July 1969, February 1971.
4. Burns, C.D. and W.N. Brabston (1968) Membrane-envelope technique for waterproofing soil base courses for airstrips-bare base support. USAE WES Miscellaneous Paper S-68-13.
5. Burns, C.D., W.N. Brabston and R.W. Grau (1972) Feasibility of using membrane-enveloped soil layers as pavement elements for multiple-wheel heavy gear loads. USAE WES Miscellaneous Paper S-72-6.
6. Joseph, A.H., R.D. Jackson and S.L. Webster (1973) Rapid road construction using membrane-enveloped soil layers. USAE WES Miscellaneous Paper S-73-5.
7. Joseph, A.H. and S.L. Webster (1971) Techniques for rapid road construction using membrane-enveloped soil layers. USAE WES Instruction Report S-71-1.
8. Peyton, H.R., C.F. Kennedy and J.W. Lund (1966) *Stabilization of silty soils in Alaska — Phase II*. University of Alaska Arctic Environmental Engineering Laboratory Research Report No. 3 for the Alaska Department of Highways — United States Bureau of Public Roads (Cooperating).

9. Quinn, W.F., D. Carbee and T.J. Johnson (1973) Membrane encapsulated soil layers (MESL) for road construction in cold regions. Presented at Symposium on Frost Action in Roads, Oslo, Norway, 1973; published by Organization for Economic Co-operation and Development, Paris.
10. Requirements for constructing membrane-enveloped soil layer (MESL) in cold regions (1973). CRREL, September.
11. Sayward, J.M. (1976) Evaluation of MESL membrane-puncture, stiffness, temperature, solvents. CRREL Report 76-22. AD A027834.
12. Schaefer, D. (1973) MESL road construction at Ft. Wainwright, Alaska. CRREL Technical Note (unpublished), December.
13. Smith, N. and J. Karalius (1973) Construction of a MESL road test section at Elmendorf Air Force Base, Anchorage, Alaska. CRREL Technical Note (unpublished), October.
14. Smith, N. and D.A. Pazsint (1975) Field test of a MESL (Membrane-enveloped soil layer) road section in central Alaska. CRREL Technical Report 260. AD A047366.
15. Webster, S.L. (1974) Construction of MESL demonstration road at Fort Hood, Texas, May 1972. USAE WES Miscellaneous Paper S-74-13.
16. Webster, S.L. (1974) Implementation package 74-2, Users manual for membrane encapsulated pavement sections (MEPS). USAE WES, June. (Prepared for Implementation Division, Office of Development, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. 20590).
17. Webster, S.L. and R.A. Andress (1976) Investigation of fabrics and bituminous surfaces for use in MESL construction. USAE WES Miscellaneous Paper S-76-14.

APPENDIX A. THE MESL CONCEPT

Fine-grained soils compacted at or slightly below optimum moisture contents can provide adequate bearing strengths for use as structural layers in pavements and embankments. However, if the moisture content increases after soil compaction there is a dramatic loss of bearing strength. The MESL concept is a method for maintaining the moisture content of the soil at the desired level by encapsulating the soil in waterproof membranes that prevent water infiltration.

The prepared subgrade is sprayed with an asphalt emulsion before the bottom membrane of polyethylene is laid. This provides added waterproofing protection in the event of membrane puncture and facilitates membrane placement during windy conditions. The first layer of soil can be placed by end-dumping or by dumping from the sides with front-end loaders. The completed soil embankment is sprayed with asphalt emulsion before placement of the top membrane. The top membrane is also sprayed with asphalt emulsion and covered with a thin layer of clean sand to blot the asphalt and to provide added protection against puncture by the paving materials and equipment.

Since the MESL concept had not previously been field tested in freezing and thawing conditions, the potential problems of heaving and thaw-weakening and their effects on the membrane and sealed joints integrities had to be evaluated.

APPENDIX B: CLASSIFICATION, COMPACTION, FREEZING AND CBR TEST RESULTS FOR FAIRBANKS SILT

Table BI. Standard compaction and CBR tests.

Sample no.	*Compaction effort*	*Water content (%)*	*Dry unit wt. (lb/ft^3)*	*Void ratio*	*Degree of saturation (%)*	*CBR (%)*
34	CE-55	5.7	102.3	0.69	22.9	25.5
5	CE-55	7.7	108.7	0.59	(88.2)	30.7
6	CE-55	8.6	112.3	0.54	44.2	84.0
9	CE-55	9.2	114.0	0.52	(92.8)	46.2
24	CE-55	9.2	114.4	0.51	49.9	86.7
10	CE-55	10.5	112.8	0.53	54.6	75.7
20	CE-55	11.2	115.0	0.50	(≈90)	50.2
25	CE-55	11.4	115.3	0.50	63.3	78.3
13	CE-55	12.3	113.8	0.52	65.7	65.0
31	CE-55	12.9	112.5	0.54	66.6	54.6
16	CE-55	13.0	116.0	0.49	73.5	70.7
26	CE-55	13.7	111.8	0.55	69.5	22.3
27	CE-55	14.4	110.3	0.57	70.3	13.3
22	CE-55	15.7	109.1	0.58	74.4	7.7
30	CE-55	18.1	104.1	0.65	77.0	4.0
33	CE-26	6.9	103.0	0.68	28.2	27.5
8	CE-26	9.4	107.6	0.61	42.9	38.3
11	CE-26	10.3	109.4	0.58	49.2(86.4)	27.6
19	CE-26	11.3	109.0	0.59	56.7	43.1
14	CE-26	12.0	110.5	0.56	58.9(82.0)	34.7
15	CE-26	13.3	109.6	0.58	63.8	42.0
4	CE-26	14.2	110.0	0.57	68.8(77.6)	29.1
1	CE-26	15.7	109.3	0.58	74.8	22.3
23	CE-26	17.0	106.3	0.63	75.2	4.2
29	CE-26	18.8	102.6	0.68	76.0	2.5
32	CE-12	9.8	99.2	0.74	36.6	15.3
21	CE-12	11.3	102.4	0.69	45.5(≈85)	10.0
12	CE-12	12.4	101.9	0.70	49.3	18.7
17	CE-12	12.9	106.8	0.62	57.8(≈85)	13.7
3	CE-12	14.5	103.8	0.66	60.4	19.1
2	CE-12	15.3	105.4	0.64	66.2(79.6)	14.3
7	CE-12	16.7	105.2	0.64	71.9	14.9
18	CE-12	17.5	104.9	0.65	74.8	9.3
28	CE-12	19.9	99.8	0.73	75.3	1.5

Note: Figures in parentheses are values of soaked samples.

Table BII. Freeze-thaw CBR tests.

Sample no.	Compaction effort	Water content (%)	Dry unit wt. (lb/ft^3)	Void ratio	Degree of saturation (%)	Type freeze thaw	Freeze thaw cycles	Total heave (in.)	CBR (%) 1-in. thaw	CBR (%) Complete thaw
FBS-1	C-12	17.0	105.8	0.63	74.3	Closed	1	0.188	–	10.4
FBS-2	C-12	17.0	105.6	0.64	73.9	Closed	1	0.200	–	–
FBS-3	C-12	14.2	104.0	0.66	59.4	Closed	1	0.166	–	–
FBS-4	C-12	14.2	104.8	0.65	60.6	Closed	1	0.200	–	20.9
FBS-19	C-12	16.0	106.2	0.63	70.6	Closed	3	(0.184,0.072,0.039)	–	–
FBS-20	C-12	16.0	105.3	0.64	69.1	Closed	3	(0.195,0.105,0.080)	13.4	13.6
FBS-23	C-12	16.4	104.9	0.65	≈95	Open	1	4.5	–	–
FBS-24	C-12	16.2	106.2	0.63	≈95	Open	1	4.8	–	–
FBS-45	C-12	9.8	101.9	0.70	39.0	Closed	1	-0.004	–	–
FBS-46	C-12	9.6	100.7	0.72	37.1	Closed	1	-0.004	19.9	16.3
FBS-47	C-12	12.0	101.2	0.71	47.0	Closed	1	-0.003	–	–
FBS-48	C-12	12.1	102.9	0.68	49.3	Closed	1	-0.005	18.1	16.2
FBS-51	C-12	12.6	105.2	0.64	54.3	Closed	1	0.006	–	–
FBS-52	C-12	12.3	105.2	0.64	53.0	Closed	1	0.001	13.9	25.0
FBS-59	C-12	17.7	106.2	0.63	78.1	Closed	1	0.234	–	–
FBS-60	C-12	17.6	106.2	0.63	77.7	Closed	1	0.286	3.4	11.3
FBS-5	CE-26	14.4	108.6	0.59	67.4	Closed	1	0.255	–	–
FBS-6	CE-26	14.4	109.2	0.58	68.4	Closed	1	0.264	–	23.8
FBS-7	CE-26	12.5	107.5	0.61	57.0	Closed	1	0.079	–	25.3
FBS-8	CE-26	13.1	107.0	0.62	59.0	Closed	1	0.083	–	–
FBS-17	CE-26	14.6	111.7	0.55	73.9	Closed	3	(0.262,0.104,0.093)	–	–
FBS-18	CE-26	14.7	110.8	0.56	72.7	Closed	3	(0.212,0.087,0.080)	27.5	26.8
FBS-31	CE-26	16.2	110.2	0.57	78.9	Closed	1	0.315	–	–
FBS-32	CE-26	16.1	109.9	0.57	77.9	Closed	1	0.238	11.5	15.3
FBS-33	CE-26	17.1	107.5	0.61	77.9	Closed	1	0.366	–	–
FBS-34	CE-26	17.2	106.5	0.62	76.5	Closed	1	0.230	6.7	2.3
FBS-35	CE-26	18.8	103.9	0.66	78.5	Closed	1	0.282	–	–
FBS-36	CE-26	18.6	103.1	0.68	76.2	Closed	1	0.317	5.3	2.1
FBS-41	CE-26	10.2	108.9	0.59	48.1	Closed	1	-0.002	–	–
FBS-42	CE-26	10.1	109.4	0.58	48.2	Closed	1	0.001	39.3	41.7
FBS-43	CE-26	10.9	107.7	0.60	49.9	Closed	1	-0.003	–	–
FBS-44	CE-26	10.8	108.4	0.59	50.3	Closed	1	0	34.0	32.2
FBS-49	CE-26	13.5	109.0	0.59	63.8	Closed	1	0.085	–	–
FBS-50	CE-26	13.4	109.9	0.57	64.8	Closed	1	0.055	36.0	27.3
FBS-55	CE-26	15.0	110.2	0.57	73.1	Closed	1	0.167	–	–
FBS-56	CE-26	14.9	111.1	0.56	74.3	Closed	1	0.200	21.3	16.7
FBS-9	CE-55	11.2	113.6	0.52	59.5	Closed	1	0.089	–	–
FBS-10	CE-55	10.9	113.8	0.52	58.2	Closed	1	0.027	–	56.9
FBS-11	CE-55	9.2	112.0	0.54	46.9	Closed	1	-0.003	–	
FBS-12	CE-55	9.2	112.2	0.54	47.1	Closed	1	-0.005	–	53.3
FBS-13	CE-55	11.5	113.4	0.52	60.8	Closed	3	(0.001,-0.003,-0.005)	–	
FBS-14	CE-55	11.6	113.6	0.52	61.6	Closed	3	(0.015,-0.001,-0.004)	36.0	44.8
FBS-15	CE-55	9.6	112.9	0.53	50.1	Closed	3	(-0.004,-0.007,-0.008)	–	
FBS-16	CE-55	9.8	112.3	0.54	50.3	Closed	3	(-0.004,-0.004,-0.005)	49.3	51.6
FBS-21	CE-55	11.6	111.1	0.56	≈95	Open	1	5.4	–	
FBS-22	CE-55	11.5	111.5	0.55	≈95	Open	1	5.2	–	
FBS-25	CE-55	14.1	115.2	0.50	78.0	Closed	1	0.150	–	
FBS-26	CE-55	14.3	113.6	0.52	75.9	Closed	1	0.166	18.0	25.0
FBS-27	CE-55	16.1	110.0	0.57	78.0	Closed	1	0.260	–	
FBS-28	CE-55	16.0	108.2	0.60	74.2	Closed	1	0.323	6.5	5.6
FBS-29	CE-55	12.6	113.6	0.52	66.9	Closed	1	0.024	–	
FBS-30	CE-55	12.2	113.4	0.52	64.5	Closed	1	0.037	58.0	49.0
FBS-37	CE-55	13.5	114.8	0.51	74.0	Closed	1	0.132	–	
FBS-38	CE-55	12.9	115.3	0.50	71.6	Closed	1	0.169	45.5	44.7
FBS-39	CE-55	15.2	112.1	0.54	77.7	Closed	1	0.193	–	
FBS-40	CE-55	15.2	113.4	0.52	80.3	Closed	1	0.224	19.1	20.3
FBS-53	CE-55	17.2	108.0	0.60	79.3	Closed	1	0.348	–	
FBS-54	CE-55	17.4	107.1	0.61	78.5	Closed	1	0.314	2.1	4.3
FBS-57	CE-55	18.6	105.3	0.64	80.1	Closed	1	0.547	–	
FBS-58	CE-55	18.5	105.5	0.64	80.3	Closed	1	0.450	0.9	3.0

Note: Figures in parentheses are for each freeze cycle.

Table BIII. Frost susceptibility test data – Fairbanks silt.

Sample no.	Compaction effort	Dry unit wt. (lb/ft³)	Saturation ratio (%)	Water content Before test (%)	Water content After test (%)	Specimen ht. Before test (in.)	Specimen ht. After test (in.)	Heave (%)	Heave rate Average (mm/day)	Heave rate 3-day max. (mm/day)
FBS-21	CE-55	111.1	95	19.0	66.2	6.0	11.4	90.0	16.0	24.5
FBS-22	CE-55	111.5	95	18.9	61.0	6.0	11.2	86.7		
FBS-23	CE-12	104.9	95	22.2	64.4	6.0	10.5	75.0	14.3	21.0
FBS-24	CE-12	106.2	95	21.5	66.4	6.0	10.8	80.0		

Table BIV. Frost susceptibility classification.

Average rate of heave (mm/day)	Classification
0–0.5	Negligible
0.5–1.0	Very low
1.0–2.0	Low
2.0–4.0	Medium
4.0–8.0	High
>8.0	Very high

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Smith, North
Construction and performance of membrane encapsulated soil layers in Alaska / by North Smith. Hanover, N.H.: U.S. Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1979.
v, 32 p., illus.; 27 cm. (CRREL Report 79-16.)
Prepared for Directorate of Military Programs, Office, Chief of Engineers by Corps of Engineers, U.S. Army Cold Regions Research and Engineering Laboratory under DA Project 4A762730AT42.
Bibliography: p. 21.
1. Anchorage, Alaska. 2. Cold environments. 3. Fort Wainwright, Alaska. 4. Membranes. 5. MESL-membrane encapsulated soil layer. 6. Polyethylene. 7. Soil moisture migration. I. United States. Army. Corps of Engineers. II. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H. III. Series: CRREL Report 79-16.

*U.S. GOVERNMENT PRINTING OFFICE: 1979—601-696/130